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14. ABSTRACT

Project Description: The value of the cooperative, dynamic environment sensing technologies lies in their relevancy to a number of present and future military applications, including bio-inspired, adaptive, reconfigurable, and synthesized sensing using cooperative sensor platforms. In this project, we aim to develop distributed algorithms to optimally sense dynamically changing environments by formulating synthetic, global sensor field of views (FOVs), mimicking biological systems such as an insect fly eye, but allowing multiple aperture configurations. Due to the desired nature of distributed networked aerial vehicles (for the purpose of scalability), the environmental sensing

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Daniel Pack
UU	UU	UU	UU		19b. TELEPHONE NUMBER
					210-458-7076

Report Title

Final Report: Acquisition of Cooperative Small Unmanned Aerial Systems for Advancing Man-Machine Interface Research

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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

<u>Received</u> <u>Paper</u>

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u> <u>Paper</u>

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

None

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Daniel Pack	0.00	No
Yufei Huang	0.00	No
Chunjiang Qian	0.00	No
Victor Maldonado	0.00	
David Akopian	0.00	No
FTE Equivalent:	**0.00**	
Total Number:	**5**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment

Technology Transfer

N/A

Final Report

Acquisition of Small Unmanned Aerial Systems for Advancing Cooperative Man-Machine Systems Research and Education

Daniel Pack, Yufei Huang, Chunjiang Qian, Victor Maldonado, and David Akopian

Department of Electrical and Computer Engineering
The University of Texas at San Antonio

Scientific Progress and Accomplishments

1. List of Appendixes, Illustrations and Tables (if applicable)

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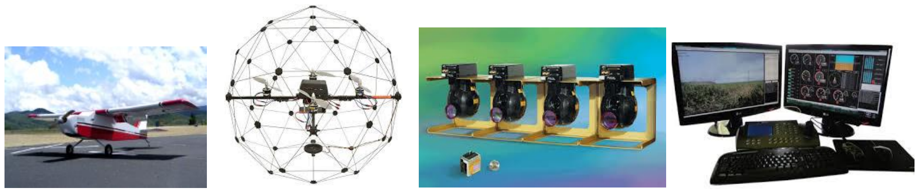
2. Statement of the problem studied

During the first calendar year, all equipment for the project, shown below, was purchased and in place to support the following projects.



(a) (b) (c) (d)

Figure 1 *Man-aerial machine system components: (a) Bruce Tharpe unmanned aerial vehicle, (b) VTOL vehicle, (c) gimbaled sensors, and (d) ground control system*

System Name	No. of items	Price
BTE-Hauler*	10	$33,540.00
10 QBall-X4-Extras# 3 Ground Stations#	1	$175,615.00
Piccolo SE Autopilots with pitot kits, deadman interface, and five altimeters	10	$104,850.00
TASE II* – Gimbal System – hardware, VPSII software, development kit, license	5	$105,550.00
Piccolo Ground Station and shipping	3	$26,550.00
	Total	$446,105.00

Table 1. Equipment purchased.

Project 1: Controlling Cooperative UAVs using Brain Waves

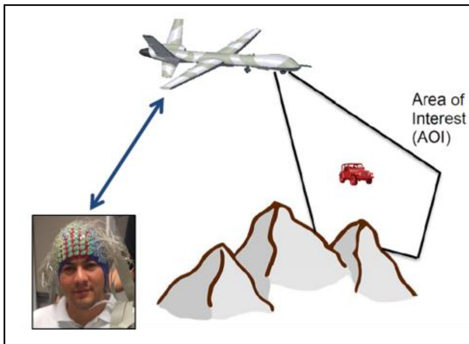


Figure 2 *Illustration of the proposed human-UAV cooperative decision system, where UAVs are controlled actively (through a thought-based command) and passively (through sensing the cognitive states) by soldier's thoughts detected by EEG sensors placed in the helmet.*

Principle Investigator: Drs. Daniel Pack and Yufei Huang, Electrical and Computer Engineering
Sponsor: Army Research Lab

Project Description: Successful military missions rely heavily on situational awareness of mission environments. While complementary autonomous sensors have provided mission information that led to improved decision making, soldiers' comprehension of complex environments, including the collective sensor information and their cognitive decisions are

often the most valuable, enabling effective and efficient execution of complex SUAV missions. Integrating soldiers into the cooperative decision making of cooperative SUAVs is imperative. Furthermore, due to pervasive threats from enemies that employ unconventional tactics, it would be highly desirable to have an integrated, human-SUAV, sociotechnical system, where SUAVs possess the ability to sense the potential risks from soldiers' high level cognitive commands and act accordingly to avert risks. Towards this end, we plan to develop and demonstrate technologies to control cooperative multiple SUAVs using brain waves of a soldier. In particular, brain waves in the form of SUAV commands will be collected by high performance electroencephalogram (EEG) sensors, supposedly placed in soldier's helmet, and transmitted wirelessly to control SUAVs. A possible scenario where a soldier controls the behavior of an unmanned aerial vehicle is shown in Fig. 2, where the soldier controls the orbit of a UAV and the onboard sensor field of views by his thoughts, allowing him and his unit freedom to move around and perform other necessary tasks. The three research areas of project are

1. Identification and classification of brain signals that correspond to cooperative UAV navigation and sensing instructions
2. Study on similarities and differences of same control signals from multiple individuals
3. Development of mapping technologies between brain waves and control signals of UAVs

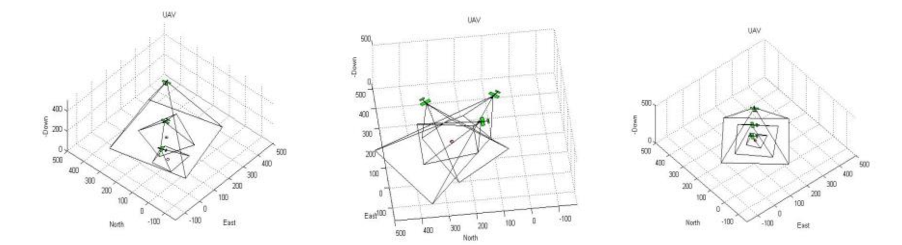
We currently have two most advanced 256-channel Biosemi® EEG headsets and also possess the experience and capability to conduct experiments to collect and detect cognitive command/performance related signals from EEG data. Powerful machine learning algorithms will be developed to detect commands (e.g., moving left or right) and high level cognitive states (alert, arousal, etc) from the EEG data.

Enhancement/Enablement of the equipment for this research: The SUAV systems play an integral part of this project and enhanced the capability to experiment the commands to multiple cooperative SUAVs using brain waves. The outcome of this project will make a direct impact on future use of unmanned systems and will further stimulate studies on human-machine cooperation in both military and civilian applications.

Project 2: Cooperative Sensor Management

Principal Investigators: Dr. Daniel Pack, Professor, Electrical and Computer Engineering,

Sponsor: Air Force Research Laboratory and Office of Naval Research



a) An FOV generated to track two mobile targets

(b) A high resolution FOV to tract a fast moving target

(c) An FOV generated to cooperatively geo-locate a stationary target

Figure 4 *Different FOVs generated by three UAVs*

Project Description: The value of the cooperative, dynamic environment sensing technologies lies in their relevancy to a number of present and future military applications, including bio-inspired, adaptive, reconfigurable, and synthesized sensing using cooperative sensor platforms. In this project, we aim to develop distributed algorithms to optimally sense dynamically changing environments by formulating synthetic, global sensor field of views (FOVs), mimicking biological systems such as an insect fly eye, but allowing multiple aperture configurations. Due to the desired nature of distributed networked aerial vehicles (for the purpose of scalability), the environmental sensing and information fusion must be performed asynchronously at dispersed locations, making the cooperative environmental sensing even more challenging. We are developing autonomous cooperative technologies to allow sensor platforms to control their poses in order to reconfigure the overall synthetic FOV to respond to the changes in their operating environments.

To generate desired synthetic FOVs and sensor models, we plan to develop bio-inspired collective sensor models. *The limitations of previous efforts are the fixed physical sensor configurations.* The mobile sensor network enables us to remove this missing capability, allowing an overall system FOV to be created with an arbitrary sensing resolution, size and configuration. Figure 5 shows three different examples where we can arrange a set of sensor resources to accomplish three different missions. The example cases depicted in the figure show the flexibility, adaptability, and redundant nature of the technologies we are proposing.

Enhancement/Enablement: One of the challenges of cooperative unmanned aerial systems is lack of experimental platforms to test and validate algorithms developed as part of this effort. The equipment will not only make it feasible to experiment our algorithms with hardware platforms, but also allow us to discover new knowledge and learn valuable insights which we cannot obtain using simulation studies.

Project 3: Assisted GPS Technology Platforms and GPS Spoofing and Interference Countermeasures

Principal Investigator: Dr. David Akopian, Associate Professor, Electrical and Computer Engineering
Sponsor: Naval Engineering Education Center (NEEC, NRL)

Project Description: In future operations, GPS receivers will be most likely challenged by hostile jamming signals or weak signal conditions. Jamming signals, in particular, can either completely deny GPS access or mislead (spoof) receivers to generate false positioning data. The goal of this project is to research and develop robust and jamming-resistant receivers including advanced interference mitigation algorithms and network-assisted GPS augmentation to support alternative channels for GPS content delivery. We work with NAVSEA to develop a military assisted GPS infrastructure to enhance receiver operations in jamming environments. Assistance data to GPS receivers, provided through wireless communication channels along with advanced receiver algorithms, improved receiver sensitivity by more than 20dB. This project exploits multiple antenna systems and assistance augmentation channels to mitigate spoofing and cross-correlation interferences. The idea is based on the fact that reported spoofing methods use direction-of-arrival (DOA). With DOA estimation, if any satellite is tracked, the receivers will be able to evaluate the direction of arrival angle using multiple antennas onboard UAVs, preventing. GPS spoofing. Assisted orbital data (ephemeris and/or almanac) also provide an alternative source of satellite locations. Receivers can estimate "expected DOAs" for satellites using orbital data and reject spoofing signals. Similar reasoning works for cross-correlation interference mitigation. To extend communication range, *the project will also investigate antenna array formation using Small Unmanned Aerial Systems (SUAS) and collaborative spoofing mitigation using cooperative multiple SUAS technologies*, as shown in Figure 6. This research will be incorporated in hands-on learning process promoted by NEEC. Particularly, testbeds and related labs will be developed to support education of related concepts, instrumentation and algorithms.

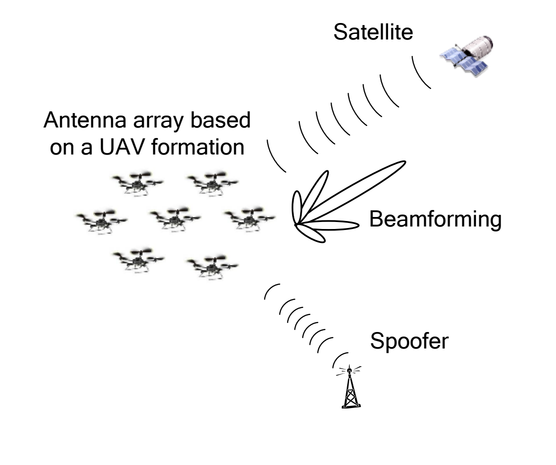


Figure 5 An illustration using a formation of UAVs for Direction

Enhancement/Enablement: With DOA measurements, the relative localization of UAVs is simplified, as all relative distances will be computed in a distributed manner at each UAV. The proposed equipment will be vital for us as experimental platforms as we perform feasibility studies to test and validate both beam-forming and DOA techniques.

Project 4*: *A Synergistic Indoor-Outdoor Environment to investigate Quad-rotor UAV-Enabled Sub-scale Testing (QUEST) of Advanced Air Traffic Management Technologies

Principal Investigators: Dr. Victor Maldonado, Assistant Professor, Mechanical Engineering

Project Description: Developing air traffic management (ATM) principles and technologies, as shown in Figure 7, to support an efficient traffic control system capable of accommodating increasing demands of future air travel is critical. Sub-scale vehicles (fixed-wing and quadrotors) are an ideal platform to test ATM concepts (in a wide variety of traffic conditions) for the following reasons: (i) low acquisition cost of the vehicle and associated electronics and autopilot systems, (ii) small footprint and stable/ precise flight characteristics (allows the implementation of a 'swarm' of quadroters operating in a relatively small space, for example), and (iii) scalability of the ATM performance from quadroters to full-scale aircraft. This project aims to advance ATM technologies by using a cooperative group of 12-15 sub-scale autonomous fixed-wing/quadroter vehicles. Some

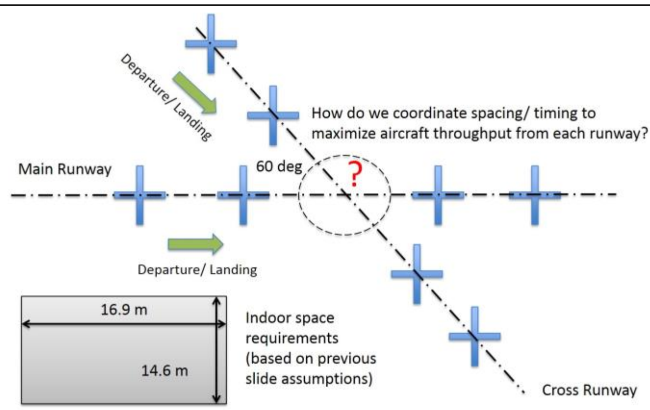


Fig. 6 Airborne Cross Runway Departure/Landing Scenario

important examples of air traffic scenarios that can be tested with sub-scale vehicles include the following:

1. Ground-based traffic or terminal-to-departure taxing traffic.
2. A mixture of landing, take-off, and taxing traffic, including "collinear airborne runway departure/landing" scenarios and "cross runway departure/landing" scenarios.

Enhancement/Enablement of the equipment for this research: We plan to use the equipment to perform testing of ATM algorithms. Conducting high-volume (12-15 SUAVs) traffic experiments in an outdoor-environment while capturing the system effect of uncertainties and with variable communication strengths among platforms will reduce the time, cost, and infrastructure necessary to implement advanced ATM concepts into air traffic management.

Project 5: Cyber-Physical Systems: Design and implementation of a cooperative man-machine system for fast emergency response in network-challenged areas

Principal Investigator: Dr. CJ Qian
Sponsor: National Science Foundation

Project Description: Through the three-year Research Experience for Undergraduates (REU) program, we are planning to train 30 undergraduate engineering students at the freshman, sophomore, and junior levels to focus on research in the areas of control, testing, and applications of unmanned cooperative aerial vehicles (UAVs). Through this UAV REU at San Antonio (UAV@SA) program at UTSA, students will gain in-depth research experience under close faculty supervision. The goal of this program is

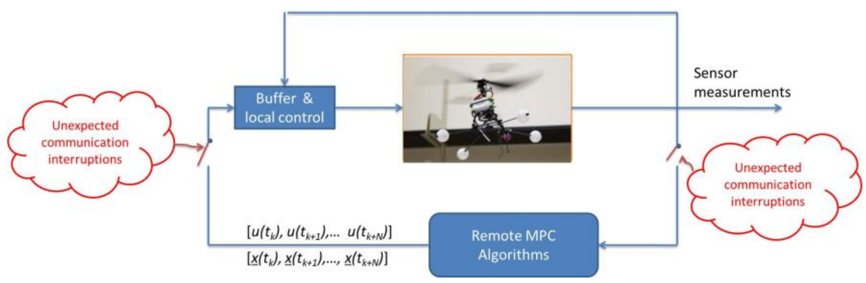


Figure 3 *Controlling a vertical take-off and landing vehicle with uncertain communication links.*

to develop a passion among participants for research in engineering and enhance their preparation to successfully pursue engineering careers. This REU program will place a special emphasis on recruiting minority, veterans, and community college students each year.

Enhancement/Enablement of the equipment for this research: With the acquisition of the proposed SUAVs, the student participants of UAV@SA will have opportunities to work on different type UAV platforms (fixed-wing, helicopters and quadrotors). The availability of different SUAVs will help students find the best test-bed and verify their designs quickly, as shown in Figure 4. In addition, students will able be able to research on the use of cooperative multiple SUAVs and associated techniques when they are working as a network system.

3. Summary of the most important results

The equipment purchase was completed by early December 2015 and plans are in place to utilize the equipment for the support of the projects mentioned in the previous section except Projects 1 and 2, as the PI for Projects 1 and 2 (Daniel Pack) has transitioned to another institution, making it difficult to continue the efforts at the University of Texas, San Antonio.

3.1 Controlling a Simulated Quad-copter using a SSVEP-based Brain-Computer Interface

The main objective of this project is to control a simple Unmanned Aerial Vehicle (UAV) using the brain activity, specifically using a Brain-Computer Interface (BCI) system. The BCI controls the take-off and launch processes of a quad-copter (the UAV) through a simulator, this is a 2-command BCI system.

3.1.1 **Introduction to SSVEP**

Several approaches have been developed for BCI and they make it possible to control an electronic device using the subject's neural activity. The approach chosen for this project is called Steady-State Evoked Potentials (SSVEP). In brief, the main principle behind this approach is that when the subject observes a visual stimulus that flickers at a certain frequency *f, the* neural activity generated in the visual cortex registers (among other activities) a sinusoidal-like signal whose frequency is also *f.* This fact makes it possible to design a BCI system that codes stimulus frequencies as commands to be sent to the output device. By accurately recognizing the frequency of the visual stimulus the subject is looking at, the coded command can be detected.

SSVEP belongs to the REACTIVE type of BCI, which means the subject is not concentrated in giving direct orders with his mind. The design of an SSVEP experiment is usually quick, simple and inexpensive. SSVEP is a very active research topic within the BCI field and several detections algorithms have been tested and diverse kind of applications have been built. Important factors that need to be carefully considered when designing a SSVEP system are listed in the following:

- The visual stimulus: shape, size, brightness, color, etc. are factors that influence the SSVEP performance; using flickering images as source of stimulus has been documented.
- Focal distance, concentration level, fatigue and other mental and physical states also affect the SSVEP performance.
- The visual stimulus is usually presented using arrays of LEDs, TVs or computer monitor. When using TV or computer monitors, the refresh rate of the screen has to be taken in consideration to correctly reproduce the flickering frequencies.
- Frequencies ranging as low as 6Hz to high as 90Hz have been successfully used for SSVEP.
- Minimum training is required for an SSVEP experiment.

3.1.2 The proposed SSVEP experiment

The objective of the experiment is to capture the sine-like signal using EEG, which is elicited when the subject watches the SSVEP visual stimulus. An illustration of our SSEVP experiment is shown in Fig. 7. The detailed design of the experiment can be summarized as follows:

- A 24 inches computer monitor is placed in front of the subject, approximately 30 – 50 cm focal distance. The visual stimulus corresponding to two flickering squares are located on the left and right borders of the screen at a central high. Each square is approximately 5 cm length per side.
- Participant is wearing an EEG cap with 12 electrodes. Several different arrangements of sensors on the scalp have been used in the literature. In our case, the 12 channels are spread

throughout several locations around the scalp in a symmetric fashion, emphasizing particularly the area of visual cortex.

- Visual stimulus has 10Hz and 15Hz flickering frequencies. 4Hz, 5Hz, 6Hz and 30Hz (easily reproducible on a standard 60Hz refresh rate monitor) were also tested but not used in the formal experiment.
- Several 25-second trials (runs) were conducted separately for 10Hz and 15Hz.
- Presentation program was implemented in MATLAB using the Psychophysics Toolbox (PTB) for the low-level communications with the computer monitor through OpenGL.
- There were two participants in the carried out experiment.

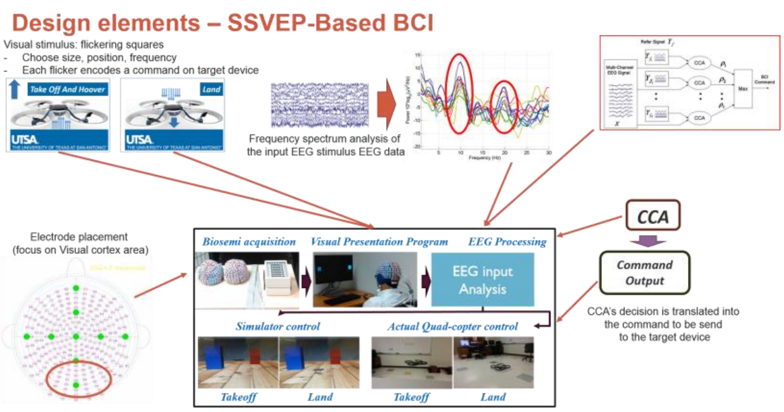


Figure 7 *Block diagram of the proposed SSVEP-based brain-controlled UAV system.*

3.1.3 EEG **acquisition and preprocessing**

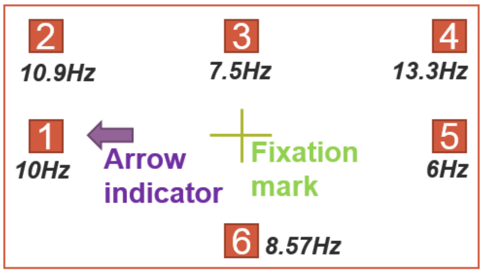
EEG signals were recorded using a Biosemi Active Two System. As mentioned before, 12 electrodes were used on the standard adult-size 256 electrodes cap. The SSVEP presentation program and the EEG recording were performed on the same computer. For the experiment, EEG data were recorded using the built-in Labview-based Biosemi acquisition software.

The data pre-processing was conducted using MATLAB and the EEGLAB toolbox. After signal was correctly loaded and trimmed (initial seconds of PTB initialization), the following operations were carried out for pre-processing:

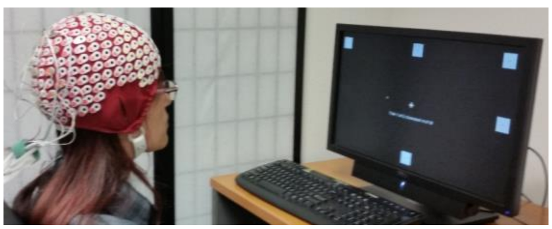
- Downsampling to 512 Hz
- FIR band-pass filter with frequencies 1Hz to 60Hz
- Averaged re-referencing

- baseline removal

After these steps of preprocessing, the power spectrum was generated to verify if there was frequency spikes at the stimulus frequency and their harmonics as suggested by the SSVEP theory. An example of a 10Hz and 15Hz frequency response for a single trial can be seen in Fig. 8.



(A)



(B)

Figure 8 *Illustration in the SSVEP BCI system that implements 6 commends.* (A) *the arrangement of the flickering and the frequencies. (B) Illustration of a participant looking at flickering visual stimulus in the real system.*

3.1.4 **Detection of SSVEP frequencies and measurement of performance**

We investigated the Canonical Correlation Analysis (CCA) algorithms for automatic detection of the SSVEP frequencies and evaluated its performance for our experiment. In a nutshell, the CCA algorithm performs correlations between a sinusoidal signal and its harmonics with the predefined frequency (e.g. 10Hz or 15Hz) and EEG recording from different channels and then finds a linear transformation that maximizes the combination of the correlations or the CCA correlation. The frequency that associated with the largest CCA correlation is detected as the stimulus frequency.

To evaluate the performance of the CCA algorithm for our experiment, each trial were spitted into a 2-second length epoch, where each epoch contains only a single stimulus. A total of 148 epochs were obtained from all the recorded data from the 2 participants. There were small differences in focal

distances and fatigue levels in the participant during recordings of those epochs. Among the 148 epochs, CCA achieved an excellent error rate of 0.041. Individually, detection of 10Hz stimulus achieved the highest detection rate in terms of a higher CCA correlation.

3.1.5 **Command generation for the quadcopter simulator**

As a final step of this project, two commands including 'take-off’ and “Land” were associated with 10Hz and 15Hz flickering, respectively. Once a frequency was detected by the CCA algorithm, the corresponding command was written in a text file by the MATLAB algorithm, which was then read by a Python script that translated these BCI commands into the actual set of instructions required to trigger the take-off and landing animations in the quad-copter simulator. A screenshot of the animation for each action can be seen in Fig. 9.

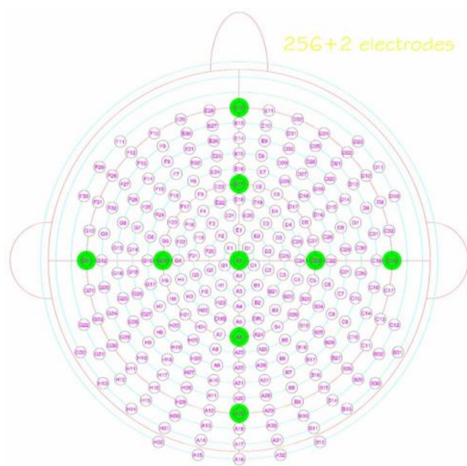


Figure 9 *The locations of the 12 electrodes used in this system.*

3.1 Publication resulted

1. “Circumnavigation for Nonholonomic Mobile Robots Using Range-based Measurements,”Proceeding of AIAA Guidance, Navigation, and Control Conference, San Diego, Jan. 2016.

2. N. Wang, C. Qian, J.C. Sun and Y.C. Liu, Adaptive Robust Finite-Time Trajectory Tracking Control of Fully Actuated Marine Surface Vehicles, IEEE Transactions on Control Systems Technology, in press, published online 11/15/2015. *DOI:10.1109/TCST.2015.2496585*

3. L. Merino, T. Nayak, G. Hall, D. Pack, Y. Huang, "Predicting the control or idle state with a likelihood ratio test in asynchronous SSVEP-based brain-computer interface systems," The Annual International Conference of the IEEE Engineering in Medicine and Biology Society, accepted, 2016.

3.2 Education and outreach activities

Overall, we have involved 5 PhD students, 4 MS students, and 1 undergraduate students in conducting research that are related to this project.

3.3 Future Plans

Upon the departure of Dr. Pack, Dr. Cao has been in charge of the equipment and coordinating the usage of the equipment.

Dr. Cao's future research plan is to test his algorithms on the QBall 2 UAV platform. One unique feature of the QBall 2 UAV platform is that it can support multi-agent navigation and control in indoor environments. The objective of conducting experiments is to understand the performance of these algorithms in real-world environments. For example, we are interested in understanding the impact of measurement uncertainties and time delays on the performance of these algorithms. The first step is to test the control algorithms of single UAVs in GPS-denied environments. The second step is to test cooperative control algorithms of multiple UAVs in GPS-denied environments. By conducting experiments on QBall 2 UAVs, we will (1) understand the advantages and disadvantages of the developed algorithms, and (2) gain more experience to conduct other experiments on the QBall 2 UAV platform.

Dr. Huang's future plan is to improve the detection performance and controller experience of the brain-UAV systems by implementing a hidden Markov model in the detection pipeline. The objective is to enable memory of past commands and given higher weights to these commands in the detection process. In addition, we plan to adapt the system to using dry sensor Cognionics EEG headset and implement the SSVEP and detection system on cell phones.

The purchased equipment also provides opportunities for undergraduate student research. Dr. Qian and Dr. Cao plan to write a proposal to National Science Foundation for a Research Experience for Undergraduates (REU) site at UTSA.